

Survey on studies about model uncertainties in small body explorations

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Abstract

Currently, the explorations of small solar system bodies (asteroids and comets) have become more and more popular. Due to the limited measurement capability and irregular shape and diverse spin status of the small body, uncertainties on the parameters of the system and s/c executions are a practical and troublesome problem for mission design and operations. The sample-based Monte Carlo simulation is primarily used to propagate and analyze the effects of these uncertainties on the surrounding orbital motion. However, it is generally time-consuming because of large samples required by the highly nonlinear dynamics. New methods need to be applied for balancing computational efficiency and accuracy. To motivate this research area and facilitate the mission design process, this review firstly discusses the dynamical models and the different methods of modeling the mostly related gravitational and non-gravitational forces. Then the main uncertainties in these force models are classified and analyzed, including approaching, orbiting and landing. Then the linear and nonlinear uncertainty propagation methods are described, together with their advantages and drawbacks. Typical mission examples and the associated uncertainty analysis, in terms of methods and outcomes, are summarized. Future research efforts are emphasized in terms of complete modelling, new mission scenarios, and application of (semi-) analytical methods in small body explorations.

Keywords: small body explorations; uncertainty analysis; Monte Carlo simulation; semi-analytical methods; micro-probe

Acronym list

- 1 **CNSA: China National Space Administration**
- 2 **DA: Differential Algebra**
- 3 **ESA: European Space Agency**
- 4 **FPE: Fokker-Plank differential Equation**
- 5 **GNC: Guidance, Navigation and Control**
- 6 **JAXA: Japan Aerospace Exploration Agency**
- 7 **LAM: Laboratoire d'Astrophysique de Marseille**
- 8 **MC: Monte Carlo**
- 9 **NASA: National Aeronautics and Space Administration**
- 10 **OD: Orbit Determination**
- 11 **ODE: Ordinary Differential Equation**
- 12 **PC: Polynomial Chaos**
- 13 **PDF: Probability Density Function**
- 14 **SRP: Solar Radiation Pressure**
- 15 **STM: State Transition Matrix**
- 16 **STO: Solar Terminator Orbit**
- 17 **STT: State Transition Tensor**
- 18 **TAG: Touch and Go**
- 19 **UT: Unscented Transformation**

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21 **1 Introduction**

22 Missions to small solar system bodies (asteroids and comets) have got much attention
23 in recent years. For the design of such missions, an important issue is to identify the
24 dynamical environment for a spacecraft's (s/c) rendezvous, approaching, orbiting
25 around and even landing on the body, which usually possesses an irregular gravity
26 field. This gives rise to a great challenge for mission design, not only with regard to
27 the highly nonlinear orbital dynamics that has been extensively addressed [1], but
28 also with regard to the capability of accurately determining the physical parameters
29 of the body, for example, mass, shape, gravity, rotation, density, etc.

30 In the early days, the small bodies could only be detected and measured by ground-

1 based (i.e., optical and radar) observations. The body's overall size, shape, spin period,
2 brightness and orbit could be estimated albeit with limited accuracies. Since the
3 1990s, distant flybys were practiced by various space agencies resulting in significant
4 improvement in the estimation of asteroids mass and density. For example the Galileo
5 (NASA) flyby of 243 Ida in 1993 [2], Rosetta (ESA) flyby of 2867 Šteins [3], and the
6 Chang'e (CNSA) flyby of 4179 Toutatis in 2012 [4]. Later on, rendezvous missions, e.g.
7 NASA's NEAR and Dawn and JAXA's Hayabusa, explored asteroids in detail at close
8 distance, greatly advancing our understanding of these small bodies. While orbiting
9 the asteroid 433 Eros in 2000, NEAR determined its gravity, mass, spin rate and
10 orientation, density and internal mass distribution [5]. In 2005, Hayabusa
11 characterized 25143 Itokawa's surface thoroughly and provided the observations to
12 develop a precise model of its shape [6]. Moreover, it touched down on the asteroid,
13 collected samples and returned them to Earth for the first time [7].

14 Nevertheless, before close encounter or arrival, the mass of small bodies cannot be
15 reliably estimated. The nucleus of comets is usually surrounded by the injected
16 dusts/gas (i.e. coma), whose densities and speeds cannot be accurately measured.
17 Thus, large uncertainties exist in the s/c flight environment, especially during its
18 rendezvous and approaching phases. Therefore, an insufficient quantification of
19 these uncertainties could lead to erroneous trade-off analyses and ultimately
20 inappropriate design of mission strategies. In the mission's preliminary design
21 process, the focus should be put on characterizing and minimizing the impact of
22 uncertainties on the design and on the performance of space systems [8].

23 There are already extensive studies about uncertainty and sensitivity analysis in
24 many aspects of science and engineering. For their detailed characterizations, the
25 reader can refer to [9, 10, 11]. Specifically, there is one review about the particular
26 topic on different uncertainty propagation methods, and their applications in space
27 situation awareness (SSA) and space flight mission designs [12], primarily focusing
28 on orbital motion around Earth. Different from these studies about Earth missions,
29 this survey provides an overview on the specific topic of the uncertainty problems of
30 s/c's motion around small solar system bodies for complementation. The outline of

this survey is organized as follows. Section 2 describes the dynamics basis, the mostly related forces and their various modeling methods. Section 3 introduces the classification of uncertainties of these forces in small body explorations. Section 4 presents an overview on the current status of typical small body missions and the related uncertainty investigations. Section 5 indicates future research prospects and challenges in both new mission scenarios and new methods. Section 6 concludes this survey.

2 The dynamics

2.1 The equation of motion

For the specific topic of small body explorations, the corresponding dynamical system can be described as

$$\ddot{\mathbf{x}}(t) = \mathbf{F}(\mathbf{x}, t) = \mathbf{F}_{deter}(\mathbf{x}, t) + \mathbf{F}_{non-deter}(t)$$

where

$$\mathbf{F}(\mathbf{x}, t) = \mathbf{f}_{central} + \mathbf{f}_{non-spherical} + \mathbf{f}_{srp} + \mathbf{f}_{outgassing} + \mathbf{f}_{thruster} \dots$$

includes all the possible forces that act on the s/c and the modeling of the primary forces is introduced in later sections. The deterministic and non-deterministic parts are represented by $\mathbf{F}_{deter}(\mathbf{x}, t)$ and $\mathbf{F}_{non-deter}(t)$, respectively. For motion around the Earth, the **solar radiation pressure (SRP)** and the atmospheric drag are the main sources for model uncertainties. **However, for motion around small bodies, both $\mathbf{f}_{central}$ and $\mathbf{f}_{non-spherical}$ include large uncertainties, especially for the non-spherical part.**

2.2 The rotation status of the small body

The rotation rate of asteroids is related to the size of the body and can range from extremely fast rotation rates (**2000 DO₈ with rotation period of 1.3 min**) to extremely slow ones (**288 Glauke with rotation period of 1200 hours**) [13]. **Slowly spinning bodies in most cases are large rubble-pile ones because otherwise they might break up if they rotate too fast. In contrast, a fastly rotating body is usually a small asteroid primarily made of monolithic rocks. Currently, some small asteroids, such as Itokawa, Ryugu and Bennu, are also demonstrated to be rubble-pile bodies by rendezvous missions that will be introduced in later sections.** A small fraction of asteroids exhibit

non-principal-axis rotation in which the rotation axis shows an additional precession and nutation, usually referred to as ‘tumbling’ motion [14, 15, 16]. Toutatis is one example that was observed by Ostro [17] with such kind of rotation, and was confirmed by the flyby data of Chang’e-2 [18]. The rotation status of a comet shares many similarities with that of the asteroid. However, one major distinction is that there is a torque from outgassing, especially during its perihelion passage. The rotational state typically evolves slowly in time and this is highly dependent on the structure and direction of the outgassing and its distribution on the surface of the comet. Detailed study on this topic can be found in [19].

The rotational status of a small body has a great influence on the orbital motion, which is more complicated than that of planets and natural moons (larger and spherical). For instance, a fast rotation, on one side, tends to average out the perturbations from the irregular gravity. Moreover, a tumbling motion makes the dynamics time varying and the orbit design difficult, the detailed discussions of which are addressed in [1].

2.3 Modeling of gravity field

The irregular shape of a small body induces a complex gravitational field, which is responsible for a strongly perturbed dynamical environment compared with that of planets. As a result of such irregularities, the design and maintenance of suitable s/c orbits can be very challenging, as the s/c might escape from or impact on these bodies due to the perturbations. In addition, with the increase of orbital radius, the s/c’s motion is less affected by the perturbation of the irregular gravity. The irregular gravity field can typically be represented by three different methods.

(a) Spherical harmonics expansion

The non-spherical gravitational potential can be expressed as an infinite spherical harmonics series expansion. Therefore, the Laplace equation of the gravity potential can be solved in terms of spherical coordinates, and it was written as [20]

$$V = \frac{GM}{r} \left\{ 1 + \sum_{n=1}^{\infty} \sum_{m=0}^n \left(\frac{R_e}{r} \right)^n P_{nm}(\sin(\theta)) [C_{nm} \cos(m\lambda) + S_{nm} \sin(m\lambda)] \right\}$$

where the reference radius R_e (usually chosen as the mean radius for a spherical

body) is here chosen as the maximum radius of the irregular and elongated body; (λ , θ) are the longitude and latitude, respectively; and r is the distance from the s/c or the particle to the center of mass of the body. P_{nm} is the associated Legendre functions. C_{nm} and S_{nm} are the spherical harmonic coefficients that are determined by the mass distribution within the body. These coefficients can be expressed in terms of inertia integrals [21], and they can be estimated, with some level of accuracy, from radar/optical observations. Since this method actually expands the potential into a spherical harmonics series, it diverges within the circumscribing sphere¹ and, therefore, the potential V is only valid outside this sphere.

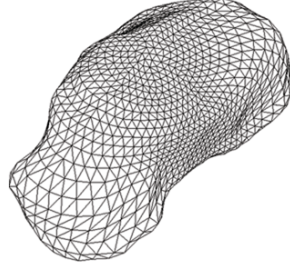
(b) Polyhedron model

A celestial body of arbitrary shape can be approximated by a polyhedron model. Werner [22] developed the closed-form solution of the potential of an arbitrary polyhedron that is split into triangular faces and edges (Fig.1). With this technique, the general formula for the potential can be written as

$$U(r) = \frac{G\sigma}{2} \left(\sum_{e \in \text{edges}} \mathbf{r}_e \cdot \mathbf{E}_e \cdot \mathbf{r}_e L_e - \sum_{f \in \text{faces}} \mathbf{r}_f \cdot \mathbf{F}_f \cdot \mathbf{r}_f \omega_f \right)$$

where G is the gravitational constant and σ is the density of the small body estimated according to the measurements of its component and the classification of its type. The two sums are the contributions from points located on all edges and all faces, respectively, which cover the entire volume of the body. The detailed explanation of all the symbols can be found in Werner and Scheeres [23]. Given a polyhedron model for complex-shape small body, its gravitational potential can be obtained, with relatively high accuracy, even on the surface of the body (in contrast with the spherical harmonics model). However, this approach is computationally heavy and assumes that the body is homogeneous by discarding any macro porosities or large voids.

¹ It contains the central body and touches each of the body's vertices.



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Figure 1 The polyhedron shape model of Itokawa with 3688 faces [24].

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A similar modeling method is called the ‘mass mascon’, in which the mass distribution of the body is approximated by a collection of point masses. The mascons were first identified and estimated for the lunar gravitational potential model [25]. The mascons model was applied to approximate the irregular gravitational field of asteroid Itokawa for JAXA’s Hayabusa mission [26]. This method has relatively low precision at the surface of the small body and it is computationally heavier than the polyhedron model, as shown in Werner’s study [23].

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(C) Geometrical shapes

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A typical geometry for approximating the shape of an elongated small body is the constant-density ellipsoid. Given an ellipsoid with semi-axes $\alpha > \beta > \gamma$ (Fig.2), its gravitational potential can be expressed as [21]

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$$U_E(\mathbf{s}) = -\frac{3GM}{4} \int_{\lambda(\mathbf{s})}^{\infty} \phi(\mathbf{s}, v) \frac{dv}{\Delta(v)}$$

15

$$\phi(\mathbf{s}, v) = 1 - \frac{s_x^2}{\alpha^2 + v} - \frac{s_y^2}{\beta^2 + v} - \frac{s_z^2}{\gamma^2 + v}$$

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$$\Delta(v) = \sqrt{(\alpha^2 + v)(\beta^2 + v)(\gamma^2 + v)}$$

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in which $\mathbf{s} = (s_x, s_y, s_z)$ is the vector from the center of the ellipsoid to the particle and $\lambda(\mathbf{s})$ is defined as the maximum real root of $\phi(\mathbf{s}, \lambda) = 0$. The integral can be numerically evaluated with the first and second kind of Carlson’s Elliptic Integrals [27]. In analogy to the polyhedron method, this potential is also valid close to and on the surface of the body. Other geometrical shapes can be used including a straight segment (characterized by its length and mass), two orthogonal segments (characterized by the length and mass of the two segments) and two contact spheres

(characterized by the radius and mass of the two sphere). The detailed descriptions of their potentials can be found in [28, 29, 30], respectively. Moreover, these geometrical shapes can be properly combined to generate more complex shapes and potentials.

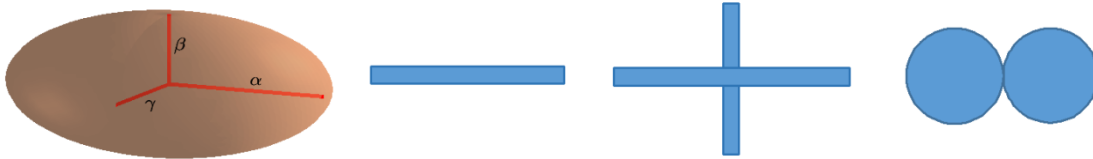


Figure 2 From left to right: an ellipsoid with three semi-axes α, β, γ ; a straight segment; two orthogonal segments; two contact spheres.

2.4 The non-gravitational forces

In addition to the irregular gravitational field of the small body, the orbiting particle or s/c is also affected by the perturbations due to solar and planetary gravitational pull, solar radiation pressure (SRP), and outgassing in case of a comet. Planetary perturbations are in general negligible, unless a close encounter between the small body and a planet occurs. In addition, for a large orbital radius, the s/c's motion is less affected by the perturbations associated with the irregular gravitational field of the object. Strong non-gravitational forces are expected when the small body approaches its perihelion, e.g. due to SRP and outgassing.

2.4.1 Solar Radiation Pressure

The SRP perturbation is stronger than the solar gravitation one especially for a s/c with a large area-to-mass ratio, since the surface area is the key element to determine the number of solar photons that interact with the spacecraft, as illustrated in Fig. 3. Systematic study has been performed on its role on s/c's orbital motion around small bodies [1]. If the s/c is far from the small body, SRP can be the main source of perturbation. For sufficiently large-mass small bodies (e.g. asteroid Eros), the perturbation from SRP is very limited. For smaller bodies, with sizes on the order of a few kilometers or less, the SRP can cause the s/c to escape or impact on the small body. Generally, the SRP can be modeled in the following three ways.

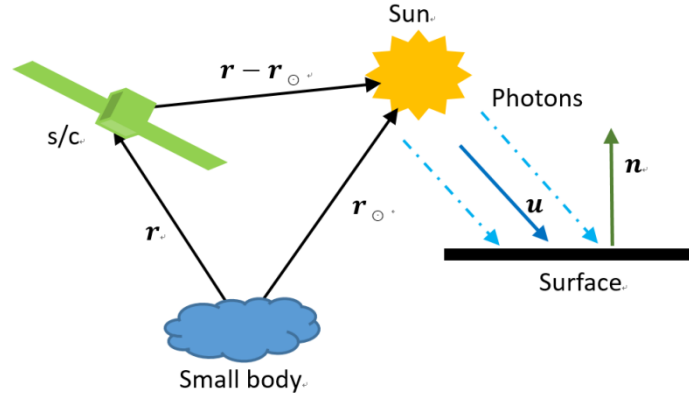


Figure 3 Geometry of the s/c orbiting around a small body and the generation of SRP.

(a) The cannonball model

The cannonball model is the simplest way to model the shape of the s/c, i.e. considering the s/c as a sphere, and therefore the s/c's attitude is excluded from the model. Since the directions of vectors \mathbf{n} and \mathbf{u} , representing the normal direction of the surface and the solar radiation direction, respectively, are parallel and the s/c is generally considered as an **ideal** reflector, the SPR strength is maximum and the corresponding acceleration is given as [31]

$$\mathbf{a}_{SRP} = -(1 + \kappa_s) \frac{\rho_{\odot} a_{\odot}^2}{c} \cdot \frac{A}{m} \cdot \frac{\mathbf{r} - \mathbf{r}_{\odot}}{\|\mathbf{r} - \mathbf{r}_{\odot}\|^3}$$

in which κ_s and A/m are the albedo and the area-to-mass ratio of the s/c, respectively; $a = 1 \text{ AU}$ is the mean distance between Earth and the Sun; c is the light speed in vacuum, $\rho = 1367 \text{ W/m}^2$ is the solar flux at 1AU; and \mathbf{r} and \mathbf{r}_{\odot} are the vector from the small body to the s/c, and from small body to the Sun, respectively.

(b) The N-plate model

For s/c with larger solar arrays and complex shapes, the N-plate model is applied for a more accurate representation of its shape. This model consists in a collection of flat plates, each of which can have different reflectivity properties. The magnitude of the SRP acceleration varies with the s/c's orientation w.r.t. the Sun and it is given as [32]

$$\mathbf{a}_{SRP} = \frac{\rho_{\odot} a_{\odot}^2}{c \cdot m} \cdot \frac{\mathbf{r} - \mathbf{r}_{\odot}}{\|\mathbf{r} - \mathbf{r}_{\odot}\|^3} \cdot \sum_{i=1}^N \left\{ A_i \cos \theta_i \left[(1 - \kappa_s^i) \mathbf{u} + 2(\kappa_s^i \cos \theta_i + \frac{\kappa_d^i}{3}) \mathbf{n}_i \right] H(\theta_i) \right\}$$

where $\cos \theta_i = \langle \mathbf{n}, \mathbf{u} \rangle$ is the dot product of the **two vectors**; A_i , \mathbf{n}_i , (κ_s^i, κ_d^i) and $H(\theta_i)$ are the area, normal vector, reflectivity properties and illumination condition for the i -th flat plate, respectively. $H(\theta_i)$ is defined as

$$H(\theta_i) = \begin{cases} 1, & \text{if } \cos \theta_i < 0 \\ 0, & \text{if } \cos \theta_i \geq 0 \end{cases}$$

(c) High-fidelity models

To include the auto occultation between different plates, Ziebart [33] proposed to use the Finite Element (FE) technique to determine the illuminated parts of the s/c for its orientation w.r.t. \mathbf{u} . Specifically, the s/c's structure is firstly defined by simple geometric shapes, which are approximated by the FE distribution of triangles or polygons. Then, a ray is projected in the direction of \mathbf{u} and its intersection with the triangles/polygons on the s/c's surface is checked. However, the computational load is heavy for an accurate approximation of the SRP, and it therefore is difficult to apply this modeling approach in real-time.

Efforts are made to improve the efficiency of the FE technique. For instance, taking advantage of the periodicity of the SRP force, Fourier series were introduced and applied to develop periodic solutions of the GOLNASS satellite [34] and also to s/c around asteroid [35] and LEO satellite [36]. For s/c on the libration point orbits or the interplanetary trajectories, the attitude profile can be more complex and the Fourier series approach was extended with spherical harmonics for approximating the SRP [37]. The details of these high-fidelity methods are given in the corresponding references.

In summary, uncertainties exist in both the modeling of the SRP and the reflectivity property of the s/c.

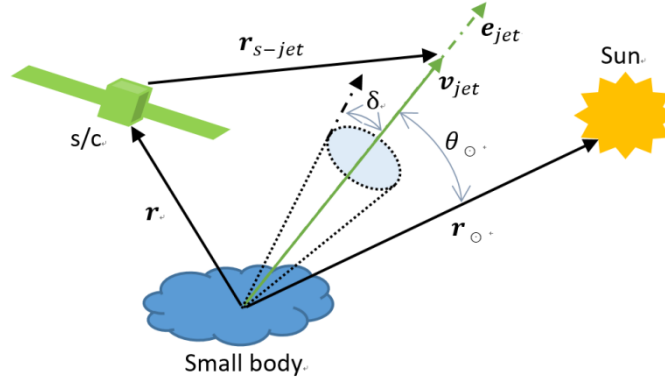
2.4.2 Outgassing

Outgassing pressure can bring significant changes in the orbital parameters of the s/c over short time spans. It can be modelled in two different ways: by a continuous model or by discrete jets, which cover the spectrum of the possible outgassing

1 environment at a comet [38].

2 (a) Discrete jets

3 This model assumes that the outgassing field is produced by multiple jets of varying
 4 strengths distributed across the surface of the comet [39]. Assuming a jet located at (
 5 $r_{jet}, \lambda_{jet}, \theta_{jet}$) (in spherical coordinate) on the surface of the comet in its body-fixed
 6 frame. A single jet can be described by the half angle δ , the velocity and direction of
 7 the outgassing \mathbf{v}_{jet} and \mathbf{e}_{jet} , as shown in Fig. 4.



8

9 Figure 4 The illustration of outgassing jet on the surface of a comet.

10 With this three dimension characterization, the acceleration from the outgassing jet
 11 on the s/c is given as [39]

$$12 \quad \mathbf{a}_{jet} = \frac{A_{jet}}{m} \cdot \left(\frac{r_{jet}}{r_{s-jet}} \right)^2 \cdot \mathbf{p}_{jet}$$

13 in which A_{jet} is the effective area of the s/c that varies with its orbital parameters
 14 since its solar panels are scheduled to point toward the Sun, and

$$15 \quad \mathbf{p}_{jet} = Q_{jet} \cdot \mathbf{v}_{jet} \cdot \mathbf{e}_{jet}$$

16 is the pressure of the outgassing at the surface of the comet assuming the orientation of the
 17 jet at ejection uniformly outwards. The mass ejection rate Q_{jet} is estimated as [40]

$$18 \quad Q_{jet} = S \cdot Q_0 \cdot f(\theta_{\odot}) \cdot g(r_{\odot})$$

19 where Q_0 is the mass ejection rate with an area equal to the surface area of the comet
 20 perpendicular to the Sun at a distance of 1 AU, and S is the jet's relative intensity

w.r.t. Q_0 , and θ is the angle between \mathbf{r} and \mathbf{e}_{jet} . The functions $f(\theta_{\odot})$ and $g(r_{\odot})$ depends on the geometry of the jet w.r.t. the Sun and are fully defined in Marsden [41]. Specifically, the mass ejection rate is not constant and varies with the distance from the Sun as well as the change of the surface topological as a result of sublimation, mass loss, or other activities over long time scales.

(b) The continuous model

The model assumes that the outgassing field is continuous and varies from its maxima at the sub-solar point to a minima at the anti-solar point on the comet. The acceleration from the continuous field outgassing on the s/c can be expressed as [38]

$$\mathbf{a}_{outgassing} = \frac{A_{jet}}{m \cdot r^2} \cdot [1 - \alpha + \alpha \cdot \cos \theta] \cdot \mathbf{p}_{jet}$$

in which $\alpha \leq 0.5$ is the parameter that indicates the outgassing pressure's variation away from the Sun line, i.e. its asymmetry property, and θ is the angle between the two vectors \mathbf{r} and \mathbf{r} . (You need to add some comments about pros and cons of this)

2.4.3 Thermal effects

Similar with the reflection of solar photons of the SRP, the absorption and re-emission of solar energy of the small body also create a tiny thrust, which produces measurable orbital changes over decades and significant orbital effects over millions to billions of years. This is known as the Yarkovshy effect [42]. In addition, this phenomenon also brings about a thermal torque that alters the rotation rate and obliquity of the small body with irregular shape, which is known as Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect [43]. These two effects are illustrated in Fig.5. Their detailed description and discussion can be found in reviews [44] and [45].

Specifically, the Yarkovshy force is computed by determining the surface temperature distribution and evaluating the thermal radiation recoil force. It primarily modified the semi-major axis of the small body's heliocentric orbit, and this modification also depends on the physical parameters of the small body, e.g. its obliquity and rotation, size and surface conductivity, etc. In particular, this effect vanishes for both very small and very large bodies. It was first measured from the s/c LAGEOS [46], whose residual along-track acceleration was found to result from the

perturbation of the thermal drag from Earth's emission of infrared radiation due to solar heating. Up to date, the most precise measurement is that of asteroid Bennu, the target of OSIRIS-Rex mission. As the estimation of Bennu's bulk density is well constrained by the Yarkovsky effect, the design challenges of this mission are eased.

The YORP effect controls both the long-term evolutions of the small body's spin vector, obliquity and the variation rate of the semi-major axis that is induced by the Yarkovsky effect. Its computation strongly depends on the shape, size, material properties, solar distance and orientation of the small body. If the YORP effect spins up the rotation fast enough, the small body should undergo fission, from which a satellite might be produced. It can be detected by a measurable change of the sidereal rotation of the small body.

Since the thermal effects mainly play roles in long timescales evolution, it will not be discussed further in this review that focuses on the orbital motion of s/c motion around a small body in a relatively short time interval. Nevertheless, they are important effects on the orbit and attitude evolutions of the small body.

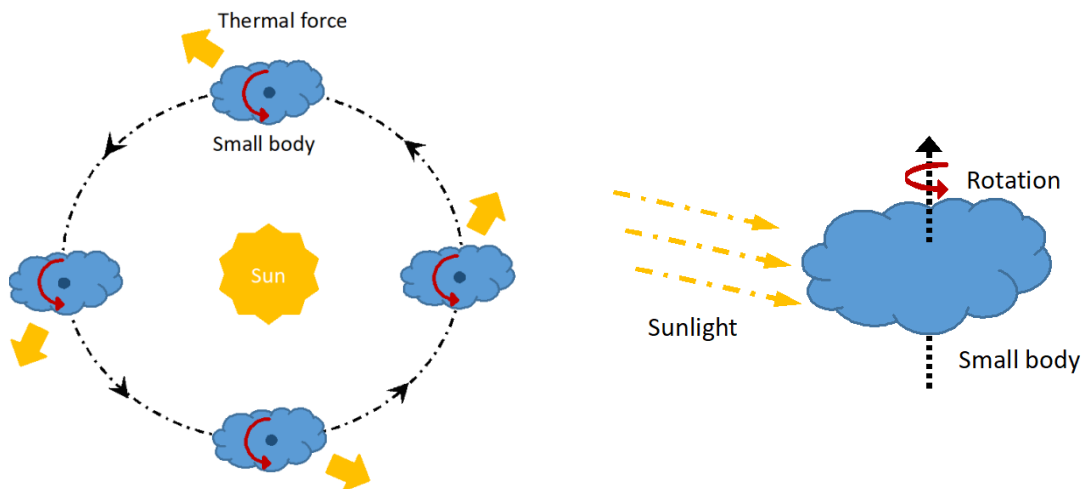


Figure 5 The illustrations of the Yarkovsky (left) and YORP (right) effects. For the Yarkovsky effect: the small body's spin axis is perpendicular to the orbital plane. A fraction of the solar insolation is absorbed only to later be radiated away, yielding a net thermal force in the direction of the wide arrows. For the YORP effect: an asymmetrical small body absorbs the sunlight falling on it and then reemits the energy in the infrared as thermal radiation in different directions. A net torque is

1 therefore generated that spins up the body.

3 2.5 Orbit design under perturbations

4 Three approaches are generally followed to design orbits around small bodies. The
5 first one consists in applying the Lagrange Planetary Equations (LPE) [20], which
6 describes the influence of the perturbing forces on the variations of the osculating
7 orbital elements. Generally, the LPE is averaged and the secular evolution of the
8 dynamics is obtained, and the frozen orbits, when orbital elements stay constant on
9 average or suffer secular motion, are identified. Studies using this method can be
10 found in [47, 48]. In the second approach the design is carried out without resorting
11 to averaging. Equilibrium points (EPs) of the full dynamical system, expressed by a
12 set of ordinary differential equations (ODEs) in which the relevant perturbations are
13 included, can be obtained in most cases by solving for the zeros of the body-fixed
14 velocity and acceleration of the s/c. Families of periodic and quasi-periodic orbits can
15 be found around these EPs by applying numerical continuation and correction
16 methods. This approach was followed in [1, 49, 50]. The third method consists in
17 applying a pure numerical procedure for direct search and continuation of periodic
18 orbits and of stable motion around the small body without the transformation of the
19 dynamics. The related research can be found in [51, 52, 53]. In general, the first two
20 approaches are applied for preliminary analysis and design of mission orbits. And the
21 last one is mainly for detailed characterization of the phase space of orbital dynamics
22 in a more specific and accurate irregular gravity field.

23 The design of the operation orbit is strongly affected by the type of perturbations
24 that are included. Different perturbations are affected by a different level of
25 uncertainties, and this uncertainty quantification plays a key role in trajectory design
26 about small bodies.

27 3 The classification of uncertainties

28 3.1 Uncertainties from gravitational forces

29 In addition to the state uncertainty from navigation and orbit determination (OD)
30 errors, our knowledge of the physical parameters of a small body is affected by large

1 uncertainties at least during the first phase of the rendezvous. During the following-
2 up approaching and orbiting **mission phases**, these uncertainties can be reduced and,
3 e.g., the 3rd and 4th order gravitational harmonics can be determined with good
4 accuracy. However, due to the contamination from possible control forces or physical
5 forces that are not well modeled (e.g., the outgassing around comets), these
6 parameters are still not completely determined. These uncertainties consequently
7 restrict the capability of OD, orbit prediction and construction, which in turn limit the
8 scientific products [54].

9 *3.2 Uncertainties from non-gravitational forces/ (Errors of the estimation of these* 10 *parameters)*

11 Other stochastic non-gravitational forces, such as the SRP, the outgassing, gas leaks
12 from attitude control system, thruster imbalance, affect the s/c motion. These forces
13 are generally several orders of magnitude smaller than gravity, and can be divided
14 into constant and time-varying contributions. The first ones can be modeled as biased
15 parameters. The latter ones can be split into rapidly varying forces, which tend to
16 average out over time, and forces with frequencies commensurate with the s/c orbital
17 period which can result into resonances and are therefore troublesome [55].

18 During the descent phase of landing missions, the physical parameters of the small
19 body are better constrained from iterations of previous phases. Nevertheless, the
20 motion in extremely close proximity is highly unstable due to the strong
21 perturbations from the body irregular gravity field and outgassing (for comets).
22 Therefore, small uncertainties in the s/c's state and maneuvers/executions can cause
23 a wide distribution of the propagated state. As a result, the braking maneuver for
24 descending is usually executed before the one planned with deterministic dynamics
25 to give enough time for the **(autonomous)** guidance, navigation and control (GNC)
26 system to counteract these uncertainties. Otherwise, the s/c might impact on the
27 small body surface even before the maneuver is performed [56].

28 **To some extent, these uncertainties will impact on choosing landing strategies. For**
29 **asteroids with small masses, it is more appropriate to 'land' through hovering or TAG,**
30 **which, for instance, is applied to both ORISIS-Rex and Hayabusha2 missions. This is**

1 due to the fact that the orbital motion of the s/c is more sensitive to these
2 uncertainties given the weak gravity attraction and more control efforts might be
3 needed to counteract them. The other option is hard landing, i.e. a lander is delivered
4 and stays on the surface of the asteroid for longer-time sample collections and more
5 detailed (even on-board) analysis, for instance, the Rosetta mission and DART. This
6 can be explained by the fact that the orbital motion of the s/c has larger resistance to
7 these uncertainties in general under stronger gravity field.

8 3.3 *Aleatory and epistemic uncertainties*

9 Uncertainties can be primarily divided into two categories: aleatory and epistemic
10 uncertainties [57]. The former results from the random nature of the system or input
11 data, while the latter one is always related to incomplete modeling of the system
12 because of a lack of knowledge. The uncertainty in the initial state, gravity field, SRP,
13 outgassing are mainly treated as aleatory uncertainties, with distribution properly
14 modeled by probability density function (PDF) [58]. The uncertainties related to the
15 gas leak, thruster imbalance and parameters of spacecraft's sub-systems are
16 considered as epistemic. They can be appropriately represented with Evidence
17 Theory [59], which is an alternative approach to the traditional probabilistic
18 representation. Rather than assuming on the probabilities or system margins, this
19 theory combines evidence and information from multiple sources and models the
20 conflicts among them, for crystallizing the inherent uncertainties [60]. This approach
21 helps formulating the mission design process into an optimization problem. For its
22 detailed application in robust engineering design, and especially for space systems
23 and space trajectories, the reader can refer to [8, 61, 62, 63]. Nevertheless, this survey
24 mainly focuses on the aleatory part of the uncertainties.

25 3.4 *Example-NEAR mission*

26 For an intuitive awareness of the state, gravitational and non-gravitational
27 uncertainties, as an example, Tables 1a, 1b and 1c give their quantitative information
28 from NEAR mission to Eros [55]. The OD error is described in the orbital frame of the
29 s/c, and the radial, along-track and cross-track directions correspond to the x -, y -
30 and z -axis, respectively, as illustrated in Fig.6. For different orbit radius, the

maximum and minimum errors are along the along-track and cross-track directions, respectively. Moreover, the closer the s/c is to Eros, the more accurate the s/c's orbit can be determined, due to the increasing strength of the Doppler data or the improving capability of optical navigation. From the estimations of the orbit and attitude of the s/c, the physical properties of Eros can be determined with a certain accuracy level. The 1σ uncertainty of the SRP coefficient is up to about 10%, and that of the gas leak (at the order of 10^{-12}) is much smaller by comparing with the GM value (at the order of 10^{-4}). The small body's internal structure and mass distribution can be characterized from the determination of the shape and gravity harmonics. The errors of the harmonic terms $C_{20}, C_{22}, C_{30}, C_{40}$, reduce by about one order of magnitude when the s/c orbit radius reduced from 200 km to 35 km. Nevertheless, the relative errors generally increase rapidly for higher degree harmonics, as it has been observed by comparing the uncertainties of the second, third and fourth order harmonics respectively. The parameters M and GM can be determined with good precision at the error of 10^{-3} . One interesting phenomenon is that their estimation is more accurate from orbit radius of 200 km than from orbits of 50 km and 35 km.

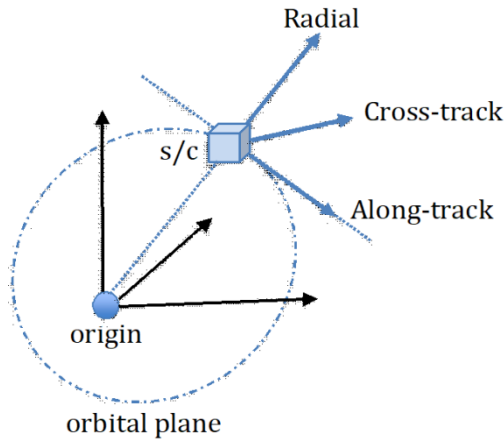


Figure 6 The radial, along-track and cross-track directions in the orbital frame of the s/c., where x -axis is in the radial direction and z -axis is in the direction of the angular momentum of the orbit and y -axis completes the right-handed reference frame.

Table 1a Spacecraft's state errors after 3 days' orbit prediction [55]

Orbit Radius/km	Radial/m	Downtrack/m	Crosstrack/m
200	856	1470	117
50	29	95	4.9
35	15	54	1.6

Table 1b Non-gravitational force parameters and their uncertainties [55]

Parameters	Nominal Values	Error ($1-\sigma$)
SRP		
<i>momentum transfer coefficient</i>	1.5	0.15
Gas leak		
<i>constant bias (km/s^2)</i>	0	5.0×10^{-12}
<i>variable modeling error (km/s^2)</i>	0	5.0×10^{-13}

Table 1c Eros gravitational estimation errors [55]

Parameters	Nominal Values	200km ($1-\sigma$)	50km ($1-\sigma$)	35km ($1-\sigma$)
Mass Properties				
$M \text{ (kg)}$	1.330×10^{16}	1.2×10^{13}	3.8×10^{13}	1.8×10^{13}
$GM \text{ (km}^3/\text{s}^2\text{)}$	8.865×10^{-4}	7.5×10^{-7}	2.5×10^{-6}	1.2×10^{-6}
Gravity Harmonics				
C_{20}	-3.03×10^{-2}	1.3×10^{-2}	9.2×10^{-3}	1.8×10^{-3}
C_{22}	$+3.78 \times 10^{-2}$	1.4×10^{-2}	6.5×10^{-4}	1.8×10^{-4}
C_{30}	$+1.05 \times 10^{-4}$	5.2×10^{-2}	2.2×10^{-4}	2.8×10^{-5}
C_{40}	$+4.09 \times 10^{-3}$	3.8×10^{-1}	1.6×10^{-2}	1.5×10^{-3}

4 The current research status of uncertainty analysis

For space missions, the primary objective of uncertainty analysis is to identify the influences of different uncertainties on the orbital motion for robust mission design.

The objective of uncertainty propagation is to estimate the distribution of state \mathbf{x} due to the presence of the uncertainties, from both the initial state and system

parameters. Denoting the PDF distribution of state \mathbf{x} as $p_x(\mathbf{x},t)$, the distribution of \mathbf{x} in space \mathcal{S} can be obtained as [57]

$$P(\mathbf{x} \in \mathcal{S}) = \int_{\mathcal{S}} p_x(\mathbf{x},t) d\mathbf{x},$$

and this integration over the whole state space is one. The time evolution of $p_x(\mathbf{x},t)$ can be obtained by writing down and solving the so-called Fokker-Plank differential Equation (FPE) [64]. However, since in orbital mechanics the dimension of the state is high (at least 6 dimensions) and the dynamics is nonlinear (especially for motion around irregular small bodies), it is difficult to solve the FPE directly and completely. Therefore, more practical techniques have been developed over the years to deal with the challenges of uncertainty propagation. In this context, three main categories, i.e. the Monte Carlo (MC) method, the linear method and the nonlinear method, can be identified. Their basic features are described in the following.

4.1 *The uncertainty propagation algorithms*

4.1.1 The Monte Carlo and linear method

(a) MC method

MC is a sample-based method [65]. Given the initial distribution of the uncertain variables \mathbf{s} as $p_s(\mathbf{s}_0, t_0)$, a number N of random samples can be generated according to this distribution. In fact, \mathbf{s} can either be the state \mathbf{x} or parameters of the dynamics, saying \mathbf{q} , or a combination of \mathbf{x} and \mathbf{q} . Therefore, the propagations of the dynamics are either with N initial states \mathbf{x}_i ($i = 1, 2, \dots, N$) and the same parameter \mathbf{q}_0 , or with the same initial state \mathbf{x}_0 but N initial parameters \mathbf{q}_i ($i = 1, 2, \dots, N$), or with the same variables of \mathbf{x} and \mathbf{q} that are certain and N samples of the uncertain variables of \mathbf{x} and \mathbf{q} . Anyhow, the N final states are statistically analyzed, from which the statistical moments (e.g. the mean and the covariance matrix) of the mapped quantities of interest are obtained. The advantage of MC is that it is easy to implement and can propagate with the full non-linear dynamics and the non-Gaussian PDF of the initial uncertainties of either states or parameters. Generally, its precision increases with the increasing number of samples, i.e., the final PDF approaches its true value if the sample number N goes to infinity. The main drawback of MC is that it is computationally expensive, especially for a large number of samples and long

propagation time, due to its sample-based characteristic.

(b) Linear method

Different from the MC method, the linear method mainly deals with dynamics with linearization, i.e. representing the nonlinear dynamics with its linearized model that approximates the dynamics of a neighboring motion w.r.t. the nominal motion using first-order Taylor expansions along this nominal motion [66]. Therefore, it is an analytical way that propagates the initial uncertainties using the state transition matrix (STM). Without generating samples, the mean and the covariance matrix can be computed directly. In particular, if the mean is zero, the covariance is obtained by mapping the initial covariance through the STM. However, for the uncertainty of the parameter, this method is not a straightforward way unless the Taylor expansion is w.r.t. the uncertain parameters that are mapped into the final state through properly augmenting the STM matrix. The accuracy of the linear method reduces for a highly nonlinear system and for variables with large uncertainties, because of its essentiality of linearizing the dynamics.

As a result of the advantages and disadvantages of the MC and the linear method, many analytical and semi-analytical nonlinear methods have been developed in the attempt to achieve a better compromise between efficiency and accuracy. The most relevant ones are reviewed in the next section.

4.1.2 Analytical and semi-analytical nonlinear methods

Based on either inherent dynamics or sample approximations, the nonlinear methods are capable of characterizing the nonlinear and non-Gaussian uncertainty propagation. Detailed mathematical definitions and descriptions of these methods and their applications in SSA are covered in Luo's review [12]. The characterizations of several typical methods are summarized as follows.

(a) Differential Algebra

With the Differential Algebra (DA) technique the flow of a set of ordinary differential equations (ODE) can be expanded in Taylor series w.r.t either the initial condition or system parameter [67]. By implementing the algebra of multivariate Taylor polynomials, this expansion is obtained in an automatic way up to an arbitrary

order without the need to write variational equations. The DA framework incorporates the algebraic, differentiation and integration operators. The availability of the Taylor approximation of the flow allows performing statistical analyses either by using samples in a Monte Carlo fashion [ref Apophis], by computing high order statistical moments (Valli paper Journal of guidance), or by directly mapping PDF (Armellin Di Lizia probabilistic IOD Journal of guidance). DA has been applied to asteroid encounter analysis [68], orbit conjunction analysis [69], s/c navigation and guidance algorithms [70], optimal control strategies [71], etc.

(b) State Transition Tensors

Uncertainty propagation by means of State Transition Tensors (STT), proposed by Park and Scheeres [72], share many similarities with the DA-based approach as it is also a semi-analytical method that approximates the flow of the dynamics with high-order Taylor series expansions. The main difference resides in the way in which the Taylor polynomials are computed. In particular, the coefficient of the SST are computed by writing and integrating higher order variational equations along with along the nominal trajectory. For this reason, the SST methodology is typically less efficient than the DA approach, resulting in lower order expansions. Once the SST are obtained by the same approaches, the mapped statistical moments can be obtained either by evaluating samples or applying analytical formulae for specific initial distributions. For instance, the mean and the covariance matrix at any time are obtained as an algebra operation given their initial conditions.

For its application, Park [73] discovered that the secular variations, rather than the short-period effects, in the dynamical model are dominant in the accuracy of uncertainty propagation. Considering the atmospheric drag force, Fujimoto [74] developed an analytical nonlinear uncertainty propagator for both conservative and non-conservative dynamical systems.

(C) Unscented Transformation

Unscented Transformation (UT) was proposed by Julier [75]. It is based on the idea that approximating the probability distribution might be easier than approximating the nonlinear dynamics. UT approximates this distribution by nonlinearly

propagating a few samples, which are a set of weighted sigma-points chosen to capture the mean and the covariance matrix of the initial distribution. The samples are propagated with the nonlinear dynamics to yield the transformed sigma-points, from which the transformed mean and covariance matrix are obtained. The symmetric (extended) set method [76] is usually employed to generate samples (rather than random ones) and determine the associated weights that are not restricted to the range $[0, 1]$. Moreover, the number of required samples is $2N+1$ (N is the dimension of the nonlinear system), which is much smaller than that required for MC, indicating its computational efficiency especially for low-dimensional system.

(d) Polynomial Chaos

The Polynomial Chaos Expansions (PC) method was first proposed by Wiener [77]. PC is also a semi-analytical method that approximates both the input and output uncertainties of a system with series expansions in random variables. Given the probability measure of the initial input, the output uncertainty can be expressed by the weighted summation of orthogonal polynomial chaos that is constructed in these random variables. The weighted coefficients are computed through intrusive and non-intrusive methods, from which the mean and the covariance of the output uncertainties can be directly obtained. This method is fast and efficient, especially for dealing with the fully non-linear dynamics and for the uncertainties that are non-Gaussian and are difficult to be represented by PDF. PC has been applied to satellite collision probability estimation [78]. Moreover, considering uncertainties in both states and system parameters, the PC method demonstrated its great advantage in identifying uncertainty evolution for hypersonic dynamics [79].

In summary, these four methods have been mainly used to analyze space missions around Earth, in terms of guidance, navigation and control, etc. Nevertheless, their applications in characterizing the impact of uncertainties on small body mission design and analysis are limited. To address this problem, the uncertainty problems and studies in the previous and ongoing small body missions are therefore presented and summarized in the next section.

4.2 Uncertainty studies in typical missions

In this section, the several uncertainty studies in previous and ongoing small body missions are presented and summarized.

(a) Hayabusa and Hayabusa-2 missions

For a small body with relatively large mass, the s/c is capable of circling around the body for long free motion arcs and the telemetry data is used to estimate the small bodies' gravity fields, e.g. Eros [80] and Vesta [81]. However, Hayabusa's target asteroid Itokawa is highly elongated and has a very weak gravity field (i.e. relatively small mass). The s/c thus performed hovering over the asteroid, for both scientific observations and gravity estimation [82]. During JAXA's Hayabusa's close proximity to Itokawa, its gravity was also determined with uncertainties (Table 2). However, for the small-mass Itokawa, the orbital motion was highly unstable as the perturbation from SRP is relatively large. Therefore, the mission applied the so-called solar terminator orbit (STO) [1], which is perpendicular to the Sun-asteroid line and quasi-stable if the SRP is dominant. For both cycling orbit and STO, Melman [83] quantified the impacts of gravity uncertainty on the evolution of them with the MC method. The motion was found to be more sensitive to the physical uncertainties of the asteroid with weaker gravity field, and for motions in mean-motion resonances² with the asteroid's rotation. These findings assist the mission planners in assessing the posed risk and designing appropriate orbits.

Launched in 2014, Hayabusa2 arrived at its target asteroid Ryugu in June 2018. Comparing with Itokawa, Ryugu has a more regular shape (diamond shaped) and also has a weak gravity field with many rubble piles. First the s/c hovered at an altitude about 20 km [84] (also called the home position), to map the asteroid for its spin orientation, rotation period, shape, obliquity and topography. Following that, the s/c performed several ballistic descents vertically to the altitude at 5~6 km, to sufficiently measuring the GM of Ryugu, during which the SRP coefficients were also estimated. However, the mass was determined still with an uncertainty of 1.3%,

² The mean motion rate of the s/c is in commensurability with the rotation rate of the small body.

1 mainly due to the uncertainties of the SRP on the s/c [84]. These operations
2 confirmed previous studies that the longer the free motion time and the lower the
3 minimum altitude bound are, the better the GM can be constrained [85]. And this
4 information is critical for planning the succeeding mission sequence, selecting the
5 potential sampling site and deploying the lander and rovers [86]. After measuring the
6 gravity, the s/c delivered the first rover MINERVA-II, which hopped among different
7 locations for science operations and sent back images of the surface of Ryugu with
8 small boulders. Then the lander MASCOT was deployed at the altitude of 51 m and
9 obtained much clearer images of the surface, which assisted selecting the sampling
10 site. During these phases, three touchdown rehearsals were performed and the target
11 marker was released for the touchdown location. Then, the s/c was inserted to the
12 'conjunction trajectory' for the solar conjunction phase, during which small insertion
13 errors might result in an undesired close approach or collision with Ryugu. Moreover,
14 using observation data during this phase, Ryugu's orbit was recalculated, which
15 allows the s/c maintain the home position more stably. The s/c completed the first
16 touchdown on the surface of Ryugu in Feb. 2019, collecting samples and returning
17 back to the home position, which requires very precise navigation and guidance. In
18 April, the s/c released an impactor on the asteroid and created an artificial crater. The
19 formation of the crater, the dispersion of the ejectors and the internal structure will
20 be observed and examined in detail. The second touchdown operation that is planned
21 in May will collect the material in the crater. The second rover MINERVA-II is
22 scheduled to be deployed in July. The s/c will depart from Ryugu at the end of 2019
23 [87]. It can be noticed that the mission operations are very complicated and require
24 high autonomy of the s/c to achieve mission objectives.

25 (b) Rosetta mission

26 Launched in 2004, Rosetta arrived at its target comet 67P/Churyumov-
27 Gerasimenko (denoted as 67P) in August 2014. During its ten-year space travel, it
28 flew by two asteroids, i.e. 2867 Šteins in 2008 and 21 Lutetia in 2010. On arrival, the
29 s/c's orbiting around the comet was found to be much more difficult than expected
30 because of its unexpected double-lobed structure separated by a narrow neck [88].

1 After having been captured by the weak gravity of 67P, the s/c orbited the comet
2 and gathered data to characterize the environment and the comet nucleus. The mass
3 and gravity field of the comet were derived from the measured velocity perturbations
4 of the s/c at distances between 10 and 100 km. The higher order of the gravity could
5 already be sensed and determined at distances below 30 km, due to the odd shape of
6 the nucleus. The values of mass and gravity field up to degree and order two are given
7 in Table 2 [89]. Compared with the GM solution for the point mass at a distance larger
8 than 30 km, there is a large error in the GM solution from the tracking data between
9 10 km and 20 km, due to the outgassing perturbation, although it is very weak.

10 In addition to the tracking data, with the assumption of constant density and based
11 on the polyhedron shape models of 67P from LAM and DLR, the gravity harmonics
12 can also be determined and are given in Table 2. It can be seen that the C_{20} and C_{22}
13 terms from the three different efforts agree well within a $3-\sigma$ standard deviation.
14 Moreover, a sensitivity analysis about the impact of the shape error on the estimated
15 harmonics was carried out and it was found that the shape-induced error was less
16 than 1% if the positioning error of the vertices of the polyhedron model is less than
17 140 m [90]. During the mission, a change of the rotation rate of 67P due to the torques
18 of solar gravitational pull and outgassing was observed. It was discovered that
19 outgassing is responsible for the majority of rotational changes and the
20 corresponding uncertainties.

21 After a few months after arrival, the s/c deployed the lander Philae in November
22 2014. Though it failed to land safely on the planned region and instead bounced to a
23 poorly illuminated region, Philae is the first lander on a comet ever and returned
24 unique science data. Then, Rosetta accompanied the comet through its perihelion and
25 through the comet's travel towards the orbit of Jupiter.

26 During the comet's perihelion passage by the Sun in August 2015, the amount of
27 water vapour released by the comet increased by a factor of ten. In addition, large jets
28 from the neck region and clouds of dust and gas (known as the coma) were observed.
29 Moreover, the plume was seen by the s/c in July 2016, as the comet was heading away
30 from the Sun at a distance of almost 500 million km. Alongside a steep increase in the

number of dust particles flowing from the comet, Rosetta also detected tiny grains of water-ice. In addition to the ice evaporation in the sunlight, other more energetic processes were believed to occur to fling that amount of dust into space. Uncovering these mechanism is still a great challenge.

Table 2 Values of GM and the 2nd order gravity coefficients of 67P with 1- σ uncertainties from the tracking data, LAM and DLR shape models [89].

Parameter	Tracking > 30 km		Tracking > 10 km
GM	666.2 ± 0.2		666.1 ± 0.4
Coefficients	Tracking data	LAM model	DLR model
C ₂₀	-0.035 ± 0.002	-0.033 ± 0.001	-0.037 ± 0.001
C ₂₁	-0.0001 ± 0.0003	0.0024 ± 0.0001	0.003 ± 0.0001
C ₂₂	0.045 ± 0.001	0.0444 ± 0.0004	0.045 ± 0.0004
S ₂₁	0.0006 ± 0.0008	-0.0012 ± 0.0001	-0.0009 ± 0.0001
S ₂₂	-0.0006 ± 0.0009	-0.0007 ± 0.0001	0.0006 ± 0.0001

(c) The OSIRIS-Rex mission

After launch in 2016, NASA's first asteroid sample return mission, OSIRIS-Rex, entered orbit around its target asteroid Bennu on December 3rd, 2018, setting the two records of orbiting the smallest body ever with the closest distance ever. On arrival, the s/c flew over the polar and equatorial regions of Bennu, to improve the estimates of its mass and spin rate and to obtain a more precise shape model, which in turn refined the follow-on trajectory design. The preliminary characterization of Bennu's mass and GM are given in Table 3 [91].

After arrival, the s/c had been orbiting Bennu for about one month at an altitude between 1.6 km and 2.1 km, which is the navigation campaign phase (orbital A phase) that aims to transform the stellar optical navigation to the landmark optical navigation and to gain experience of navigating in close proximity to a small body. During this phase, small particles near Bennu were detected and determined not to pose risk to the s/c. After that, the s/c began the detailed survey phase to map the

global properties of Bennu and select the candidate sample sites, which will be narrowed down during the follow-up orbital B phase when the s/c orbits around Bennu the closest ever with the radius of 1 km and performs radio science experiments [92]. As the gravity of Bennu is so weak, forces of the SRP and the thermal pressure from Bennu's surface (i.e. the Yarkovsky effect on the s/c) become much more relevant and can perturb the s/c in its orbit. Therefore, STO was chosen to be the nominal science orbit. Sensitivities of the terminator orbits to the maneuver execution errors were analyzed based on the averaged dynamics and tested against MC simulations. The frozen-STO, which is fixed in the Sun-asteroid rotating frame, is found to be more robust against the execution errors [93].

After a few planned rehearsals, the sample will be retrieved from the asteroid during the touch and go phase (TAG) [94], after which the s/c will drift away from Bennu to a safe distance and stay a longer time until 2023, for characterizing the effects of YORP and Yarkovsky on Bennu's rotational and orbital motion, respectively. The rotation rate of Bennu is estimated to accelerate continuously at $3.63 \pm 0.52 \times 10^{-6}$ degree/day², probably due to the YORP effect [95]. Considering errors from measurement noise, ground station location, navigation, maneuver executions, asteroid's ephemeris, gravity modeling and SRP, the position and velocity were accurately estimated with accuracies at meter and centimeter per second levels, respectively (Table 3b) [94]. These small navigation errors were due to more accurate restriction of the small body's parameters in the final landing phase. Taking into account these uncertainties and with the assumption of Gaussian distribution, a TAG strategy with a closed-loop control algorithm was developed. Its robustness was assessed with MC analysis, and it was found to meet the requirement of delivering the s/c to within 25 m of a given TAG site with about 3σ uncertainty. **However, the predetermined TAG design might be refined and changed due to data gathered from Bennu since arrival.**

Table 3a. The Bennu bulk density and related quantities with $1-\sigma$ uncertainties [91]

Bulk density ρ (kg/m ³)	1190 ± 13
Mass M (10^{10} kg)	7.329 ± 0.009

$$GM \text{ (m}^3/\text{s}^2\text{)}$$

$$4.892 \pm 0.006$$

Table 3b. Navigation uncertainty (3- σ) [94]

	Position uncertainty (m)			Velocity uncertainty (m/s)		
	radial	along-track	cross-track	radial	along-track	cross-track
Nominal GM	0.529	3.132	0.633	0.173	0.035	0.077

(d) AIDA mission

The Asteroid Impact and Deflection Assessment (AIDA), consisting of NASA's Double Asteroid Redirection Test (DART) mission and ESA's Asteroid Impact Mission (AIM), aims to demonstrate the kinetic impactor deflection technique. DART will impact the secondary of the binary asteroid Didymos. **AIM is the s/c that is designed to observe the whole impact process and the binary system, and it will release two CubSats for additional scientific observations** [96]. Unfortunately, AIM did not go into a further study case and is now simplified as Hera mission in the study case [97], while DART is planned to launch in 2021 [98]. Reliability analyses of uncertainties on both orbiting and landing phases have been performed during the preliminary mission design.

For the orbiting phase, the parameters of the asteroid, e.g. mass, shape, rotation, and the s/c's mass, surface area and reflectivity, were varied to evaluate their influences on the stability and lifespan of orbital motion in the equatorial plane of the asteroid [99]. Since the duration of most small body missions is about several months (that is much shorter than that of Earth missions) for practical purpose, the stability is therefore characterized as the orbit's duration of free motion arcs (without maneuvers) for radio or laser tracking and navigation [99]. By using MC simulations, retrograde orbits were found to allow about 90 days' free motion arcs. **Moreover, during the landing phase, the separation error of the deployment of the CubeSats was found to dominate the uncertainties of their GNC errors and the density of the secondary body as well as the landing precision [100].**

In summary, the uncertain gravity field of the small bodies and the execution errors were found to have obvious impacts on orbital motions. Moreover, almost all of the

1 studies were made by applying the MC method, which is time-consuming and not
2 appropriate for autonomous navigation and onboard calculations. Therefore, more
3 efficient methods have to be introduced and explored to approximate the results of
4 MC simulations with the required accuracy. The advantages and drawbacks of
5 applying the nonlinear methods, described in Section 3.1.2, to small body
6 explorations will be addressed in the following section.

7 **5 The prospects of future research**

8 To meet challenges from new mission scenarios, two main aspects can be addressed:
9 the complete modeling of the uncertain dynamics, and the application of new
10 methods. Both of them are discussed in this section.

11 *5.1 Complete modelling*

12 For orbital motion around asteroids, to accurately determine the forces and
13 perturbations on the s/c, the knowledge of the asteroid needs to be improved, in
14 terms of its shape, density, rotation state, mass ejection, etc. However, these
15 parameters might be changed due to the Yarkowsky and YORP effects during a long
16 time period. Therefore, for very long-duration missions, this problem should be
17 considered and managed as model uncertainties.

18 Specifically, the uncertainty of the rotation state of the small body has a great
19 influence on the detailed mission planning, as mentioned in Section 2.2. Thus, during
20 the proximity mission operations it should be included in the uncertainty modeling
21 and its influence should be characterized in detail for robust mission design. For
22 comets, the outgassing is a significant perturbation on its nearby orbital motion, and
23 it becomes stronger during the comet's perihelion phase. However, it is difficult to
24 predict due to the insufficient knowledge about the material properties and its
25 injecting speed, etc. Moreover, similar with that of SRP, the perturbation of the
26 outgassing also relates to the surface area of the s/c that the outgassing force acts on.
27 The inclusion of it in the modeling and its investigation is highly required, because it
28 can contribute to a more robust mission design.

29 In addition, as the altitude of the s/c increases, the magnitude of the SRP force
30 becomes large and comparable with that of the gravity force [1, 101]. Therefore, the

SRP also plays an important role on the s/c's orbital motion and its uncertainty should be analyzed in detail, especially for s/c with large solar sails.

5.2 *New mission scenario - microprobes*

Recently, microprobes (e.g. CubeSats, NanoSats) and their constellations are popular candidates for future asteroid missions because of their low cost [102]. With the limited-area solar sails and low/micro-thrusts, the transfer from high altitude orbits to low ones is resultantly slow. Therefore, the s/c might be captured by the main ground-track (or mean motion) resonances during its slow crossing of the resonance region [103]. This brings new challenges that are not present for a s/c with large maneuver capability. In addition, the lower the resonance order² is, the stronger the motion is influenced, due to the fast accumulation of perturbation from the irregular gravity field within a short period of time. For instance, the deviation of the position from the nominal value in the STOs around Itokawa was found at local maxima around the 2:1, 3:1 ground track resonances [9]. The dynamics in the resonance region is rich in terms of resonance splitting, overlap and chaos [104]. It is possible that the s/c is temporarily or permanently captured in these regions. Very limited research has been performed on this topic, which is far from being enough [104]. Specifically, the probability of the s/c's capture into the resonance region is highly dependent on its states and the forces (e.g. SRP, gravity, maneuvers) exerting on it, all of which have uncertainties. It is required to put efforts on including these uncertainties in the resonance analysis. Moreover, due to the limited maneuver and operational capabilities of microprobes, the uncertainty analysis for evaluating mission risks and avoiding unnecessary fuel consumption is therefore very important.

5.3 *Application of the (semi-)analytical methods*

Uncertainty analysis (UA) characterizes how input uncertainties affect model outcomes. In addition to UA, the other demand of applying new methods is the determination of the individual uncertainty's contribution to the outputs, which is called the sensitivity analysis (SA). The critical parameters or initial conditions that drive/dominate the system dynamics can be identified from SA [60]. For UA, the

² Given the $M:N$ resonance, the resonance order is defined as the value of $|M - N|$.

1 distributions are chosen based on our understanding of the environment and space
2 systems. In contrast, for SA the distributions can be simply selected to fully explore
3 potential variable effects. However, the implementations of both UA and SA are
4 closely connected and complementary to each other in mission design. Since the SA
5 is essential to identify the dominant uncertainties for different small body mission
6 phases (e.g. rendezvous, orbiting, hovering, proximity and landing, etc.), the most
7 suitable mission orbits, control and navigation algorithms can be better identified
8 during the design phase by addressing SA. Nevertheless, the systematic UA and SA
9 require more efficient methods for large amount of simulations, to achieve the
10 required accuracy with the highly nonlinear dynamics of small body explorations.

11 For the methods described in Section 3.1.2, the DA and STT are based on the
12 expansion or approximation of the dynamical model (dynamics-based), while in
13 contrast the UT and PC are sample-based with no requirement on simplifying the fully
14 nonlinear dynamics. One main shortage of the dynamics-based methods is that it is
15 difficult to go to very high order approximations for a high-fidelity system, due to
16 computational complexity. **The other drawback is that they are local methods that are**
17 **not capable of handling dynamics with large uncertainties. This however can be**
18 **solved by using an automatic domain splitting method that automatically splits the**
19 **current polynomial expansion into two polynomials whenever its truncation error**
20 **reaches a predefined threshold. The detailed description and application can be found**
21 **in Wittig et al. [105].** Moreover, they require the dynamics to be continuous and
22 differentiable. Hence, they encounter problems for perturbations with discontinuity,
23 e.g. SRP (the shadow effect) and the discrete outgassing jet. The drawback of the
24 sample-based methods is that the number of samples (e.g. UT) and the number of
25 expansion terms (e.g. PC) change linearly and exponentially with the dimension of
26 input uncertainties, respectively, and is very computationally expensive for large-
27 dimensional uncertainties of complex system. **In addition, UT propagates Gaussians**
28 **at the second order while it still assumes that the output is Gaussian, which causes**
29 **truncation error. On the other hand, for PC, the determination of the polynomial**
30 **coefficients needs solving ODEs or least-squares regression or integration on**

1 tensor/sparse grids, which suffers the curse of dimensionality.

2 New challenges for their applications arise in small body explorations. Firstly, the
3 dynamics is highly nonlinear as a result of the irregular gravity field and the rotation
4 status of the small body. Secondly, compared with those of Earth, uncertainties of the
5 model parameters (gravity and physical parameters) are larger because of the limited
6 measurements available and the resultant restricted accuracy. Therefore, for
7 methods based on series expansions such as the DA, to achieve accurate
8 approximation of the propagated orbits, the expansion has to go to a higher order.
9 For sample-based methods, their computational efficiencies are sensitive to the
10 dimensionality of the dynamical system. More samples and high order expansion of
11 the inputs are required to accurately capture the input uncertainties with large values
12 and numbers, especially for the highly nonlinear dynamics.

13 *5.4 Other research directions*

14 For small body explorations, due to the long distance of the s/c w.r.t. Earth and the
15 short time that is allowed for landing or sampling operations, autonomy is highly
16 required. Therefore, robustness plays a significant role. However, the accurate
17 quantification of uncertainties together with the efficient and accurate handling of
18 them can make sure that the mission is designed and performed robustly.

19 For instance, as mentioned in Section 1, uncertainties of the s/c's state spread in a
20 wide range during the descent phase. This is an ideal scenario for applying and testing
21 feedback control algorithms [106], due to the relatively weak gravity attraction of the
22 small body and resultantly larger thrust/maneuver authority of the s/c. The control
23 operation allows for more accurate and robust soft-landings. However, robust
24 treatment of uncertainties will be essential to reduce the resultant control efforts.
25 Their qualitative and quantitative relations should also be the focus of future research.

26 **6 Conclusions**

27 In this survey, the status of the small body explorations is firstly presented. Then, the
28 dynamics of the orbital motion around the small body is described, together with the
29 approaches of modeling different forces and the possible uncertainties. Afterwards,
30 the sources of uncertainties are analyzed and are classified into the aleatory and

epistemic categories, including uncertainties in s/c's state, operations, gravity and outgassing of the small body, SRP, etc.. For the arrival, orbiting, hovering, proximity and landing phases, the main uncertainties for each phase are discussed. The MC, linear method and nonlinear methods of uncertainty characterizations are described. The nonlinear methods are analyzed to have great potential and advantages of application in small body missions. Future research efforts, e.g. complete modeling of uncertainties and applying new and more efficient methods and microprobes, are put forward for reference.

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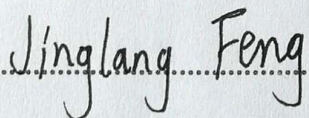


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